Muon Collider lattice design

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APS April Meeting

April 17, 2021

Introduction

LHC is currently the only collider operating at the energy frontier.

Still unanswered questions call for more powerful tools for the post-LHC era.
Costs for building and operating larger facilities is the main obstacle to their realization.

Technological advancements and new ideas are key ingredients for overcoming the impasse of high costs.
Is a Muon Collider a more affordable alternative to hadron and lepton colliders both at the energy frontier and as Higgs factory?

Muon Collider

First proposed by Budker (1967), the idea of a Muon Collider relies on the feasibility of fast cooling and the interest for such a facility has renewed every time progress has been done on this topic.

- **The mainly U.S. based Muon Collider Collaboration has produced a long paper (PRST-AB 2, 1999) defining the parameters for a Muon Collider Facility for different physics cases.**
- **Around 2007 studies resumed in the US and Europe.**
- **We are experiencing a "third wave"...**

Pros:

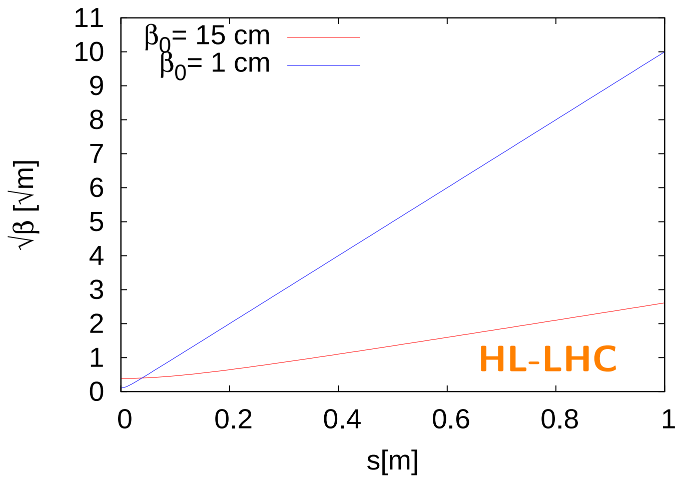
- **Point-like as $e^{\pm}$ $\rightarrow$ the whole beam energy is carried by the interacting particles.**
- **207 times heavier $\rightarrow$ no SR and no beamstrahlung at the same energy.**

Cons:

- **Short lifetime ($\tau = \gamma$ 2.2 μs) requires**
  - **large number of muons to be produced;**
  - **6D cooled and quickly accelerated.**
  - **Bkg.**

Lattice Challenges

- **Low β^*:**
  - **Strong IR quadrupoles and large $\hat{\beta}$:**
    - **large chromaticity;**
    - **large sensitivity to misalignments and field errors.**
- **High density: $N \approx 2{\times}10^{12}$ per bunch.**
- **Protection of magnets and detectors.**



For the High Energy collider:

- **$\sigma_\ell \leq \beta^*$ to avoid hour-glass effect.**
- **Expected large momentum spread ($\approx$ 0.1%) requires**
  - **small $|\alpha_p|$ ($\approx 1{\times}10^{-5}$) over the momentum range to achieve short bunches with reasonable RF voltage;**
  - **sufficient Dynamic Aperture ($\gtrsim 3\sigma$) in presence of strong sextupoles and large dp/p.**

IR chromaticity correction

Montague chromatic functions $W_{x,y}$

$$W_z \equiv \sqrt{A_z^2 + B_z^2}$$

$$B_z \equiv \frac{1}{\beta_z^{(0)}} \frac{\partial \beta_z}{\partial \delta_p} \qquad A_z \equiv \frac{\partial \alpha_z^{(0)}}{\partial \delta_p} - \alpha_z^{(0)} B_z \qquad (z = x/y)$$

$\Delta p/p$

$$\frac{dB_z}{ds} = -2A_z \frac{d\mu_z^{(0)}}{ds} \quad \text{and} \quad \frac{dA_z}{ds} = 2B_z \frac{d\mu_z^{(0)}}{ds} - \beta_z^{(0)} k$$

$$k \equiv \begin{cases} +(K_1 - D_x K_2) & \text{(hor.)} \\ -(K_1 - D_x K_2) & \text{(vert.)} \end{cases} \qquad \begin{aligned} K_1 &\equiv \text{quad. strength} \\ K_2 &\equiv \text{sext. strength} \end{aligned}$$

- $A_z(s)$ becomes non-zero when going from the IP (A_z=B_z=0) through the IR quads.
- $B_z(s)$=0 as long as $d\mu_z^{(0)}/ds$=0.

A sextupole close to the FF quads (large $\beta_z \rightarrow d\mu_z^{(0)}/ds$=0) corrects A_z and keeps B_z=0.

- horizontal dispersion must be generated in the IR for instance by dipole components in the IR quads
  - they may help sweeping secondary charged particles.

Second order chromaticity

$$\xi_z^{(2)} = \frac{1}{8\pi}\int_0^C ds\,(-kB_z \pm 2K_2\frac{dD_x^{(0)}}{d\delta_p})\beta_z^{(0)} - \xi_z^{(1)}$$

lin. chrom.

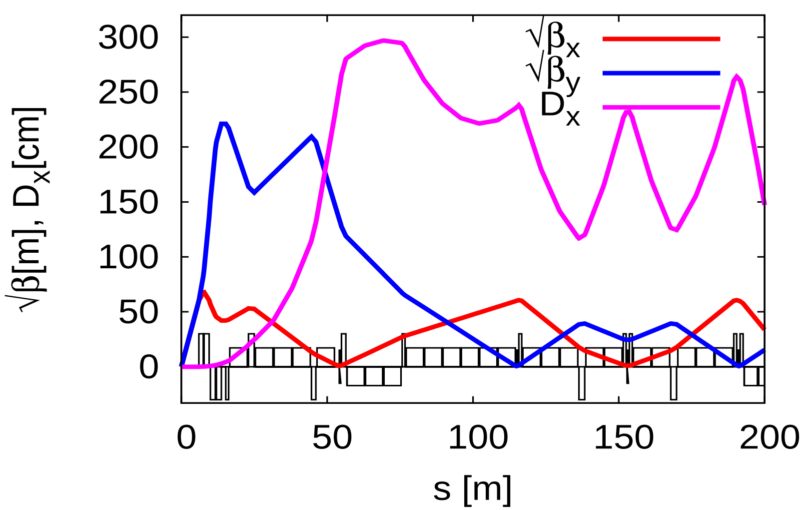
$\rightarrow$ **chromatic functions $B_{x,y}$ and $dD_x^{(0)}/d\delta_p$ must be both compensated!**

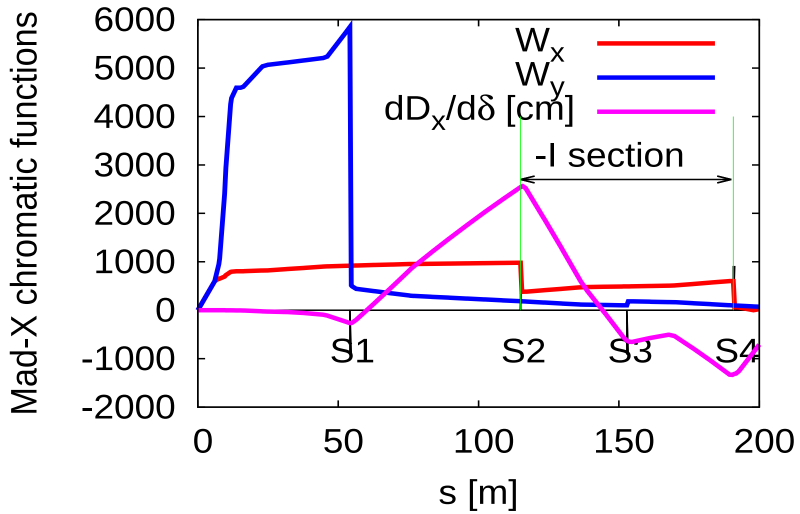
Indeed conventional chromaticity correction in the arcs did not deliver the needed performance.

- **With $\hat{\beta}_y \gg \hat{\beta}_x$ (focusing first in the horizontal plane)**
  - **W_y is first corrected by a single sextupole at $\Delta\mu_y \approx 0$ from IP and very small β_x (for normal sextupole it ensures that the effect on detuning with amplitude and resonance driving terms are small, a consequence of $H = ax^3 - 3axy^2$).**
  - **W_x is corrected with one sextupoles at $\Delta\mu_x = m\pi/2$ from IP and $\beta_x \gg \beta_y$;**
    - **a "twin" sextupole at (pseudo)$-I$ reinforces β-wave correction and cancels its geometric aberrations.**
- **2d order dispersion may be corrected by sextupoles at a low $\beta_{x,y}$ locations.**
- **D_x at all sextupoles should be as large as possible.**

Interaction Region for 1.5 TeV c.o.m.

Interaction region with a doublet FF with ℓ^*=6 m for E_{beam}=750 GeV.





(Y. Alexahin et al.)

- $\hat{g}$ = **250 T m^{-1}**
- $\hat{B}$ = **10 T, reduced to 8 T at high β locations.**

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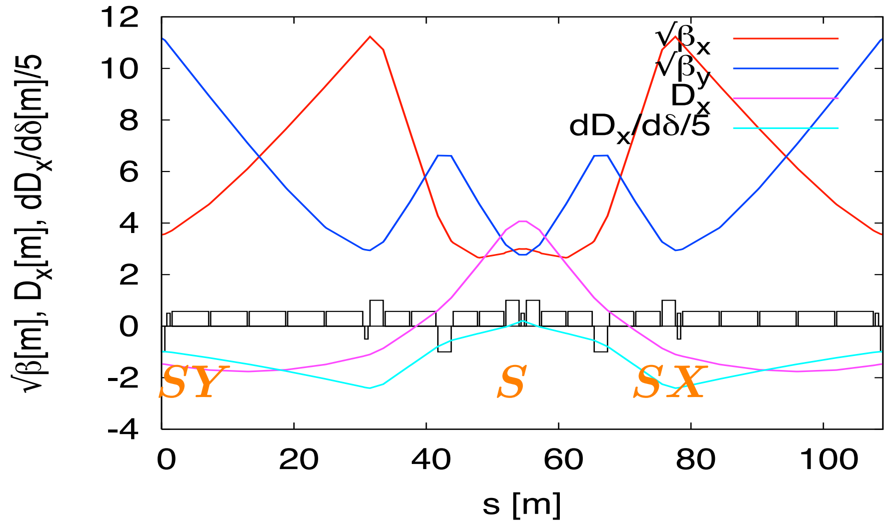
Arc cell

- **Large (positive) IR contribution to α_p must be compensated in the arcs.**
- **α_p must be small over the momentum range.**

A possible arc cell



(Y. Alexahin et al.)

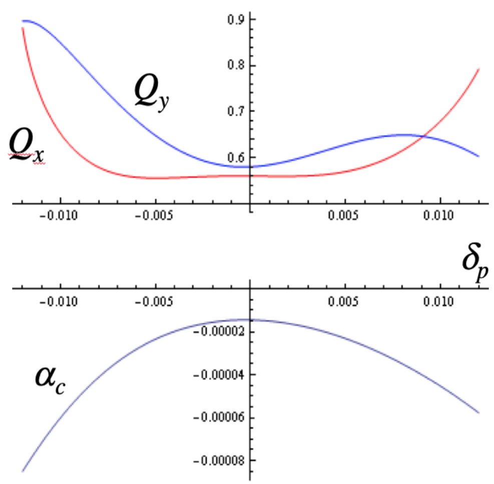
- **Orthogonal chromaticity correction.**
  - **Phase advance and number of cells adjusted for canceling 3^{rd} order driving terms.**
- **Quads and sextupole in the middle control α_p and $d\alpha_p/d\delta_p$**

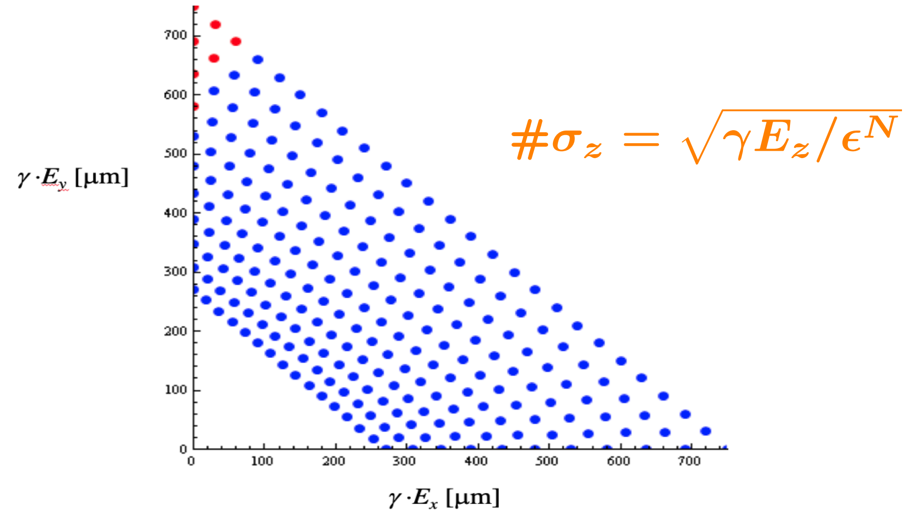
IR and arc are matched through a dispersion-free tuning section which

- accommodates injection and RF stations;
- allows β^* tuning.

Lattice performance

Octupoles and decapoles added in the IR chromaticity correction section.



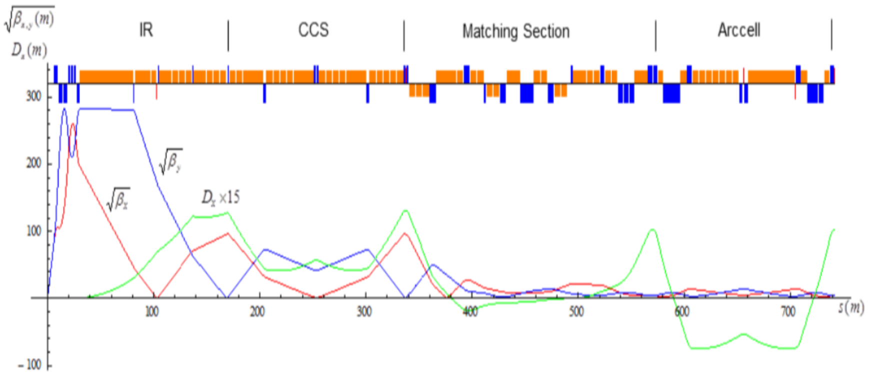


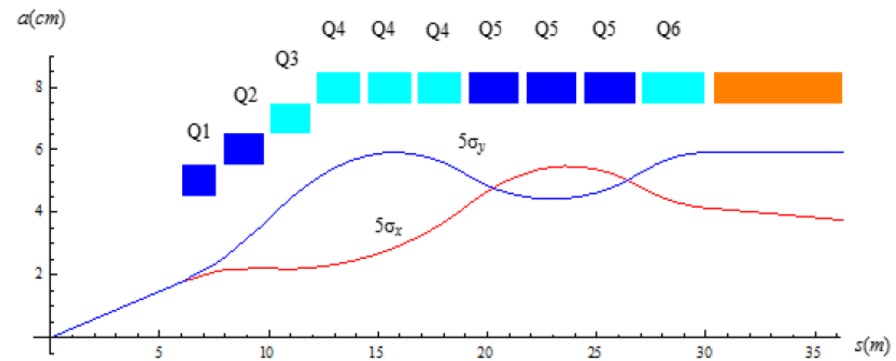
(Y. Alexahin et al.)

- Momentum acceptance of $\pm 1.2\%$ exceeds requirement.
- DA (on energy) is $\approx 5\ \sigma$ ($\epsilon_\perp^N$ 25 μm).
  - Multipole errors, fringe fields and beam-beam may impact it.

3 TeV c.o.m. case

- $\mathcal{L}$ must increase as $\approx E^2 \to \beta^*$ must decrease as $\approx 1/E$
  - Limits on FF quadrupoles gradient and aperture rend the 750 GeV scheme non extendable to 1.5 TeV beam energy. D-F-D triplet and F-D-F-D quadruplet design considered for β^*=5 mm and ℓ^*=6 m.



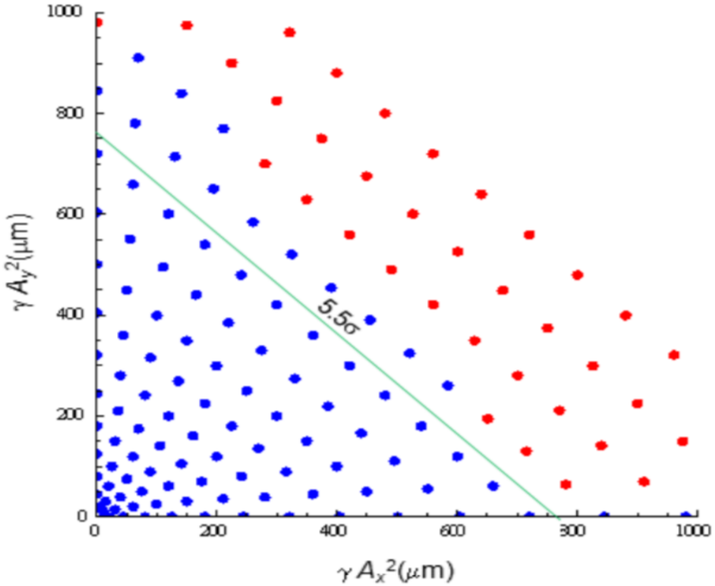


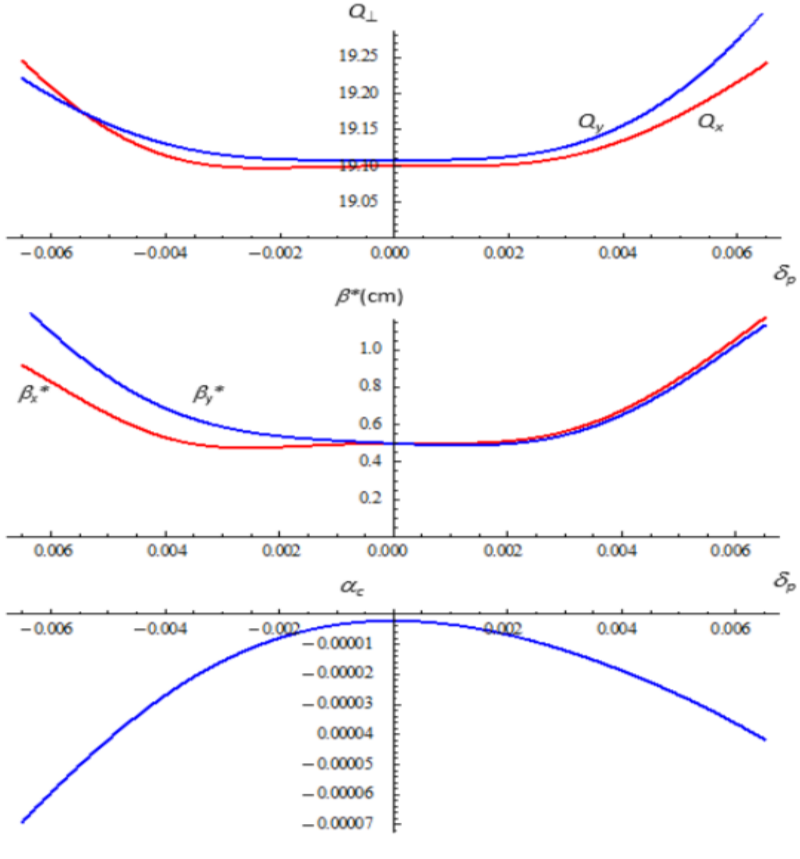
(Y. Alexahin et al.)

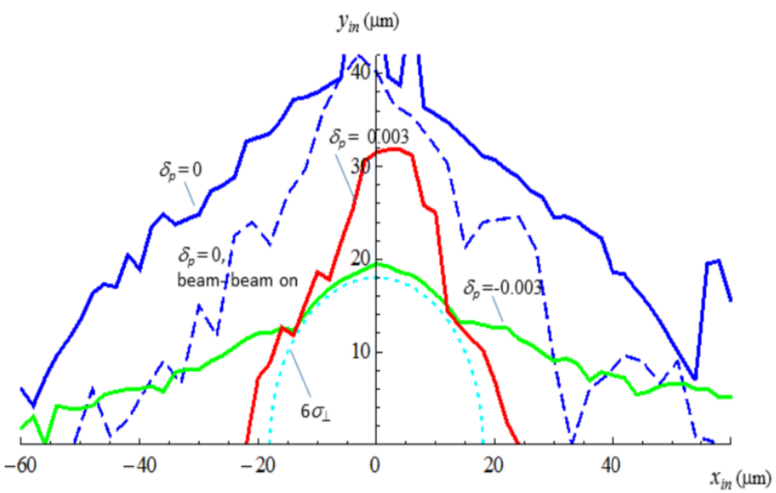
quads radius includes 2 cm for absorbers

- Chromaticity correction as in 1.5 TeV version.
- Neutrinos hot spots limit length of straight sections to about 1 m $\to$ long arc quadrupoles replaced by combined function magnets.

Lattice Performance for the 3 TeV MC





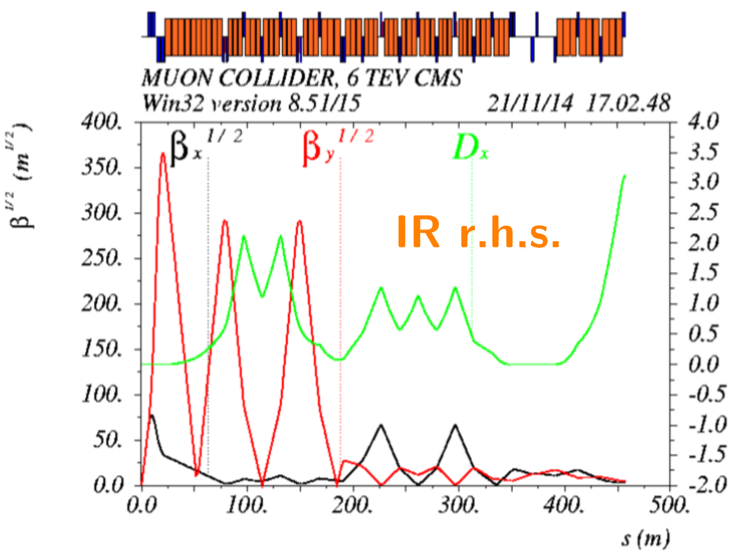


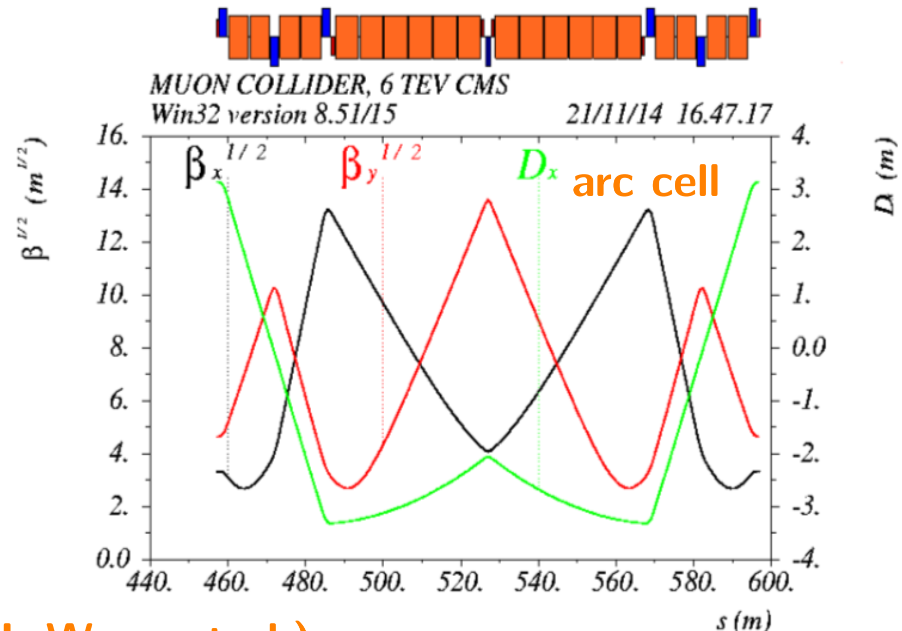
(Y. Alexahin et al.)

6 TeV MC

A ring design pushing field values with 1.5 cm space for liners.

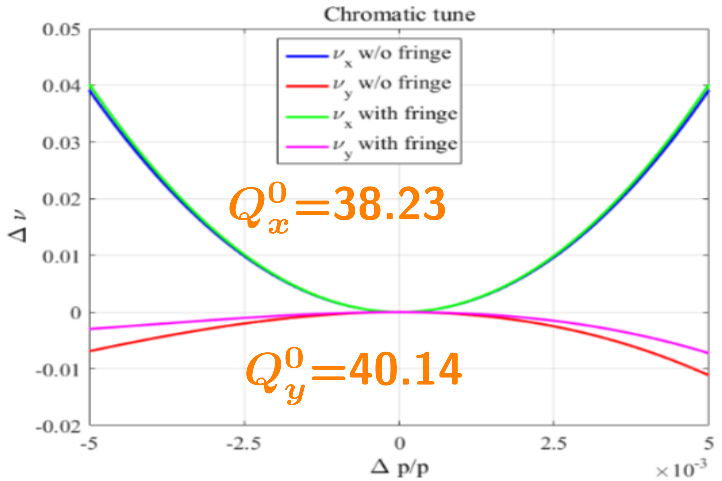
- **20 T dipoles, 15 T pole-tip field for quadrupoles.**
- **FF doublet (cut into variable aperture slices), ℓ^*=6 m, β^*=1 cm.**
- **IR chromaticity corrected by <u>two</u> non-interleaved sextupoles pairs separated by $-I$ transformations.**
- **Dispersion suppressor section matches IR to arcs: it hosts RF, injection etc.**

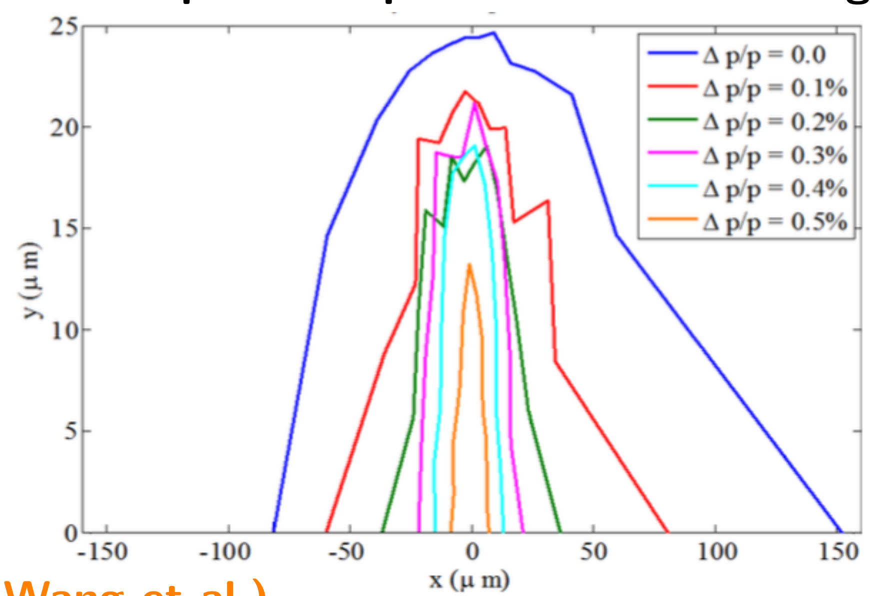




(M.H. Wang et al.)

- The design doesn't address the α_p issue.
- Initially poor DA (mainly due to $\Delta\nu_y$ with amplitude and momentum) was improved by adding:
  - Octupole at D_x=0 and large β_y correcting detuning with amplitude;
  - Opposite polarity octupole pair at large D_x and β_x and connected by a $-I$ map for correcting third order ξ_x;
  - Two weaker sextupoles, in addition to each IR sextupole, compensate their finite length effect.





(M.H. Wang et al.)

- momentum range: $\pm 0.5\%$.
- Large DA: $\approx 3\sigma$ for δ_p=0.5%, in presence of dipoles and quads fringe fields.

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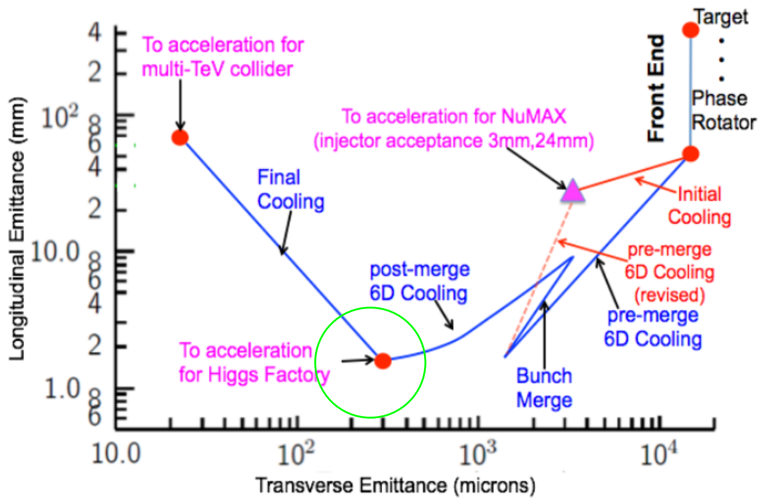
Higgs Factory

- Low beam energy (63 GeV) but 4 MeV Higgs peak width requires small energy spread ($\approx 3\times 10^{-5}$):
  - Small α_p is nomore required.
  - Stopping muon cooling where longitudinal emittance is minimum, leaves a large transverse emittance ($\epsilon_\perp^N \approx 300\mu$m).



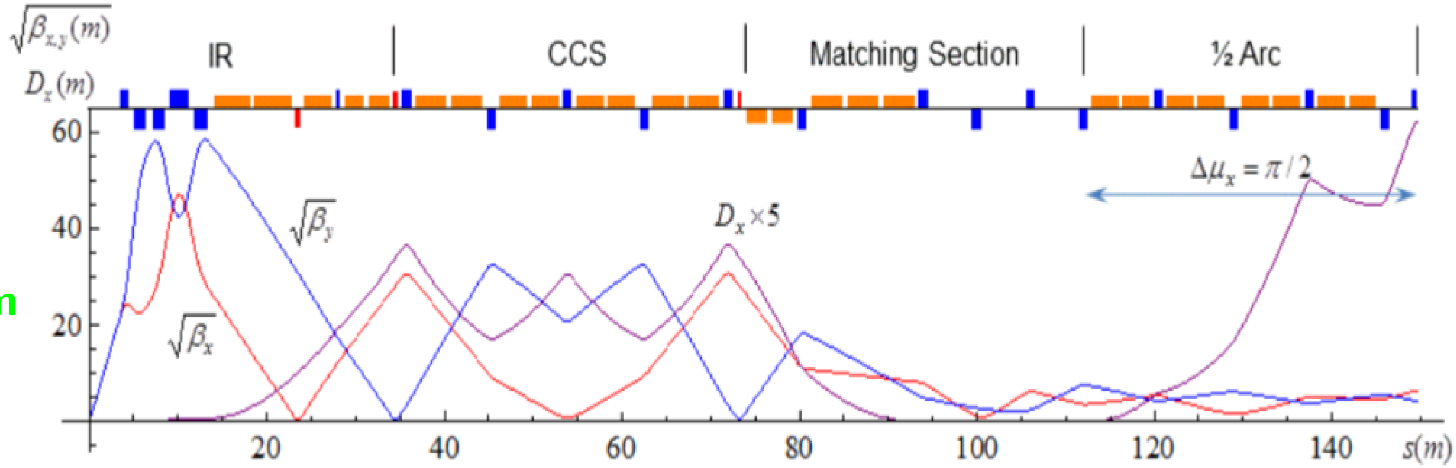
- Needed $\mathcal{L}$ requires still a small β^* ($\approx$cm) resulting in a large beam size at the FF quads.
- Small energy spread must be defended against a variety of threats:
  - microwave instability: it calls for a large α_p;
  - longitudinal beam-beam:

$$\frac{\Delta V}{V_{RF}} \approx -\frac{|e|NC}{4\pi h V_{RF} {\beta^*}^2}$$

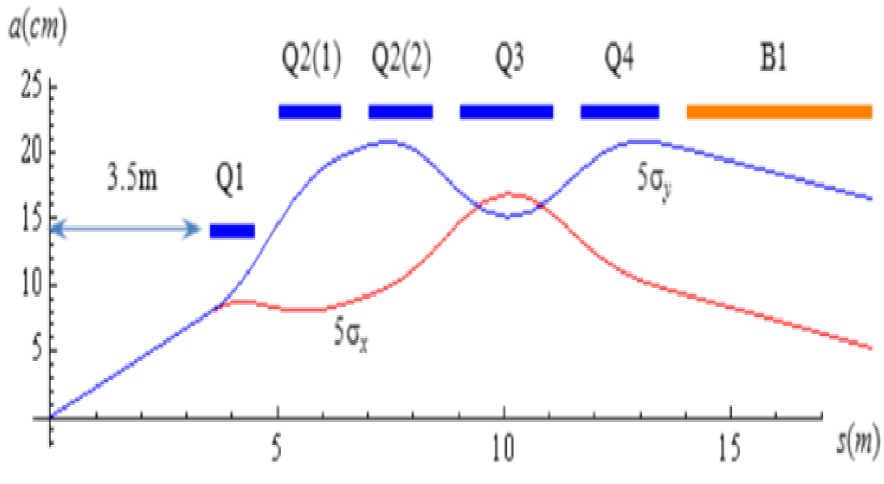
it may require a higher harmonic RF.

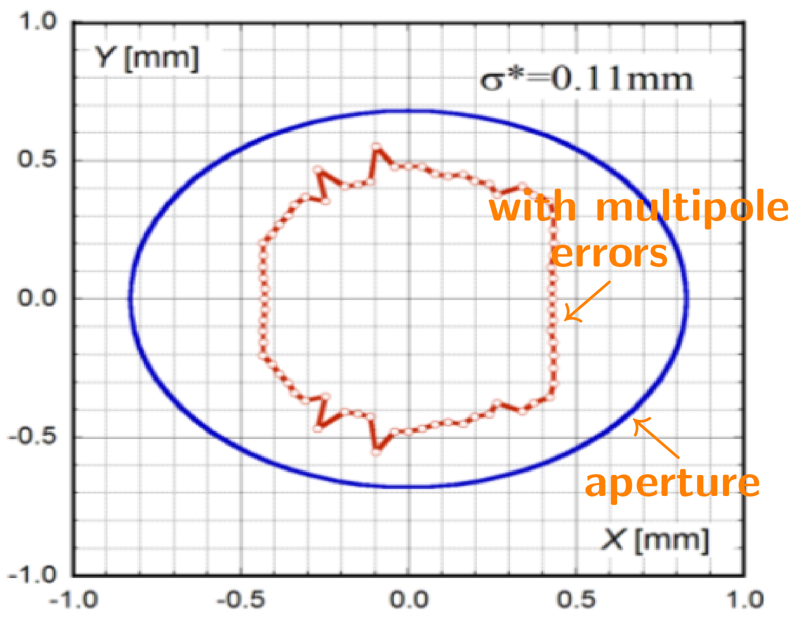
Similar to 3 TeV design with quadruplet FF and 3 sextupoles for local chromaticity correction.

β^*=2.5 cm



(Y. Alexahin et al.)





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Design parameters

	Higgs Factory	High Energy Collider		
Beam energy [TeV]	0.063	0.75	1.5	3
$\mathcal{C}$ [Km]	0.3	2.5	4.3	6.3
IP's #	1	2	2	2
β^* [cm]	1.7	1	0.5	1
σ_ℓ [cm]	6.3	1	0.5	1
α_p	0.079	-1.3 $\times 10^{-5}$	-0.5$\times 10^{-5}$	-1.2$\times 10^{-3}$
$\epsilon_\perp^N$ [μm]	300	25	25	25
σ_p/p [%]	0.004	0.1	0.1	0.1
n_b	1	1	1	1
N_μ	4$\times 10^{12}$	2$\times 10^{12}$	2$\times 10^{12}$	2$\times 10^{12}$
f_{rf} [GHz]	0.2	1.3	1.3	-
V_{rf} [MV]	0.1	12	50	-
Repetition rate [Hz]	15	15	12	15
Average $\mathcal{L}$[cm^{-2}sec^{-1}]	8$\times 10^{31}$	1.25$\times 10^{34}$	4.6$\times 10^{34}$	7.1$\times 10^{34}$

Summary

Some of the challenges related to the design of a Muon Collider and possible approaches for overcoming them have been shown.

- **The 1.5 TeV and 3 TeV collider designs are relatively mature. The related studies on magnets, energy deposition and beam-beam effects haven't pointed out to showstoppers.**
  - **Both designs assumed fields compatible with already available technology: 10 T pole-tip for quads, 10 T dipoles.**
- **There is a promising complete design for a 6 TeV collider with β^*=1 cm and somewhat pushed magnet fields.**
  - **It should be possible to solve the α_p by modifying the arc cells.**
- **Higgs factory case: is it competitive with a e^+e^- collider?**